Edge Charge Asymmetry in Top Pair Production at the LHC

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Abstract

In this brief report, we propose a new definition of charge asymmetry in top pair production at the LHC, namely the edge charge asymmetry (ECA). ECA utilizes the information of drifting direction only for single top (or anti-top) with hadronically decay. Therefore ECA can be free from the uncertainty arising from the missing neutrino in the $t\bar{t}$ event reconstruction. Moreover rapidity Y of top (or anti-top) is required to be greater than a critical value Y_{C} in order to suppress the symmetric $t\bar{t}$ events mainly due to the gluon-gluon fusion process. In this paper ECA is calculated up to next-to-leading order QCD in the standard model and the choice of the optimal Y_{C} is investigated.

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I. INTRODUCTION

Being the heaviest fermion ever known, the top quark has many unique features and it is thought to be closely related with the new physics beyond the standard model (BSM). After top quark was discovered in 1994, the measurement of its angular distribution is the critical issue because it reflects the coupling structure of the interactions. As such forward-backward asymmetry $A_{\rm FB}$ in top pair production is one of the most interesting quantities. Sometimes $A_{\rm FB}$ is also called the charge asymmetry when CP conservation in top sector is assumed. Tevatron has already observed some experimental and theoretical inconsistency in $A_{\rm FB}$ measurements [1–11]. It stirred up immediately many investigations in the BSM [12–28]. However, so far the precision of $A_{\rm FB}$ is limited by the small sample collected at the Tevatron and it is hard to make a clear judgement. In order to confirm/exclude the inconsistence, it is natural to expect that top quark $A_{\rm FB}$ will be measured with higher precision at the LHC, which is the top factory. If the top quark $A_{\rm FB}$ inconsistence with the SM prediction can be confirmed at the LHC, it will be a sign of the BSM.

However LHC is a forward-backward symmetric proton-proton collider, so there is no straightforward definition of $A_{\rm FB}$ as that at the Tevatron which is a forward-backward asymmetric proton-anti-proton collider. New observable that can reveal the top-antitop forward-backward asymmetry, which is generated at partonic level for example $q\bar{q} \to t\bar{t}$, is needed at the LHC. There are some existing observables in literatures that can fulfill this need [6–8, 29–38]. However, each of them poses some advantages and disadvantages. Generally speaking, the favorite decay chain to tag the top quark pair is $t\bar{t} \to b\bar{b}2jl\nu$, which implies that the top (or anti-top) decays semi-leptonically in order to label the mother particle charge. Although some techniques can be adopted, such as requiring the invariant mass of the lepton and the neutrino should be just equal to the W mass, the undetected by-product neutrino may still cause the non-negligible uncertainty during the event reconstruction. The precision of forward-backward asymmetry will be limited by this uncertainty. As such it is better not to use the momentum information of semi-leptonically decaying top (anti-top) quark. In this paper only hadronically decaying top (anti-top) quark momentum information is utilized.

In order to isolate the asymmetric events from the symmetric ones which is mainly due to the symmetric gluon-gluon fusion processes, some kinematic region should be chosen. The

requirement that the rapidity of top is larger than a critical value $Y_{\rm C}$ can greatly suppress the symmetric cross section. In this paper, we define a new charge asymmetry observable in $t\bar{t}$ production at the LHC, namely the edge charge asymmetry $A_{\rm E}$ (cf. Eq. 1). In some sense $A_{\rm E}$ is an optimized version of the central charge asymmetry $A_{\rm C}$ [6–8, 38]. $A_{\rm E}$ is free from the uncertainty of neutrino momentum reconstruction and much larger than $A_{\rm C}$ since $A_{\rm E}$ is much less polluted by the symmetric $gg \to t\bar{t}$ contributions.

In section II, we present the definition of the edge charge asymmetry $A_{\rm E}$. Its relation with the central charge asymmetry $A_{\rm C}$ is discussed. In section III, numerical results for $A_{\rm E}$ up to NLO QCD is calculated. In section IV, we give our conclusions and discussions.

II. THE EDGE CHARGE ASYMMETRY IN TOP PAIR PRODUCTION AT THE LHC

As mentioned in above section, the new edge charge asymmetry $A_{\rm E}$ satisfies: (a) utilizing single top (anti-top) kinematical information rather than the top pair information to avoid the uncertainty in neutrino reconstruction; (b) suppressing symmetric $gg \to t\bar{t}$ background events as much as possible. The edge charge asymmetry $A_{\rm E}$ is defined as

$$A_{\rm E}(Y_{\rm C}, Y_{\rm max}) \equiv \frac{\sigma_{\rm t}(Y_{\rm C} < |Y_{\rm t}| < Y_{\rm max}) - \sigma_{\bar{\rm t}}(Y_{\rm C} < |Y_{\bar{\rm t}}| < Y_{\rm max})}{\sigma_{\rm t}(Y_{\rm C} < |Y_{\rm t}| < Y_{\rm max}) + \sigma_{\bar{\rm t}}(Y_{\rm C} < |Y_{\bar{\rm t}}| < Y_{\rm max})} \equiv \frac{\sigma_{\rm E}^{A}(Y_{\rm C}, Y_{\rm max})}{\sigma_{\rm E}(Y_{\rm C}, Y_{\rm max})} \tag{1}$$

where rapidity $Y_{\rm C}$ is the border between the edge and the central regions, and Y_{max} is the maximum value that the detector can cover. An ideal detector has $Y_{max} = \infty$. $A_{\rm E}$ is the ratio of the difference and sum of the number of t and $\bar{t}$ events that fall in the edge region of the detector. Here t and $\bar{t}$ are unnecessarily from the same quark pair.

$A_{\rm E}$ depends on the choice of $Y_{\rm C}$ and Y_{max}. Y_{max} is determined by the geometry of the detector and $Y_{\rm C}$ should be taken at its optimal value to obtain the most significant $A_{\rm E}$. We will investigate the optimal $Y_{\rm C}$ at LHC in section III.

As a comparison, the so called central charge asymmetry is defined as [6–8, 38]

$$A_{\rm C}(Y_{\rm C}) \equiv \frac{\sigma_{\rm t}(|Y_{\rm t}| < Y_{\rm C}) - \sigma_{\bar{\rm t}}(|Y_{\bar{\rm t}}| < Y_{\rm C})}{\sigma_{\rm t}(|Y_{\rm t}| < Y_{\rm C}) + \sigma_{\bar{\rm t}}(|Y_{\bar{\rm t}}| < Y_{\rm C})} \equiv \frac{\sigma_{\rm C}^{A}(Y_{\rm C})}{\sigma_{\rm C}(Y_{\rm C})}. \tag{2}$$

It can be seen that the difference between $A_{\rm E}$ and $A_{\rm C}$ is that they are defined in different regions. As symmetric $gg \to t\bar{t}$ events are mostly located in the central regions, the expected value of $A_{\rm E}$ should be larger than that of the $A_{\rm C}$. For the $t\bar{t}$ events at the LHC, in the edge

region $Y > Y_{\rm C}$, the number of t events will be a bit larger than the number of the $\bar{t}$ events. Oppositely, in the central region $Y < Y_{\rm C}$, the number of $\bar{t}$ events will be a bit larger than the number of the t events. If we cover the total kinematical region, the asymmetric t and $\bar{t}$ events in central and edge region will be canceled completely out.

In the SM, the leading order QCD $t\bar{t}$ producing cross section is symmetric, and the asymmetric $t\bar{t}$ cross section arise from the next-to-leading order (NLO) QCD at the partonic level, which has already been well studied in many literatures. In the calculation of $A_{\rm E}$, the asymmetric cross section in the numerator is up to NLO QCD, the total cross section in the denominator is taken as the LO QCD symmetric cross section Fig.1, so as $A_{\rm E}$ is up to $O(\alpha_s)$. Other higher order correction such as electro-weak contribution is ignored here. The calculation are carried out with the help of FeynCalc, FormCalc, and QCDLoop [39–41].

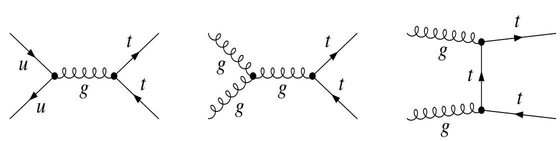


FIG. 1: Typical Feynman diagrams for $t\bar{t}$ pair production at LHC at $O(\alpha_s^2)$.

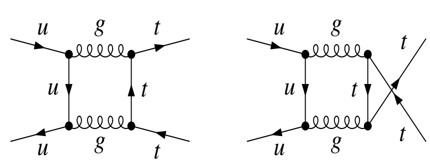


FIG. 2: Typical NLO virtual Feynman diagrams which contribute to asymmetric cross section.

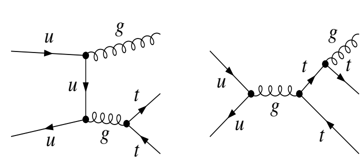
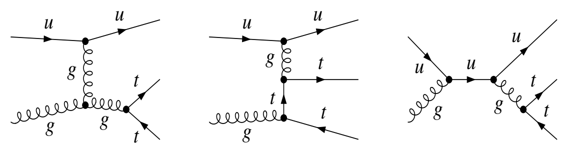
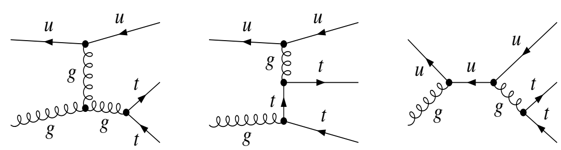


FIG. 3: Typical real gluon emission Feynman diagrams which contribute to asymmetric cross section.



(a)



(b)

FIG. 4: Typical Feynman diagrams of $ug \to ut\bar{t}$ (a), and $\bar{u}g \to \bar{u}t\bar{t}$ (b).

Up to NLO QCD, $\sigma_{\rm E}^{A}$ gets contributions from: (1) the interference among virtual box in Fig. 2 and the leading diagrams for the process $q\bar{q} \to t\bar{t}$ in Fig. 1; (2) the interference among initial and final gluon radiation diagrams of $q\bar{q} \to t\bar{t}g$ in Fig. 3; and (3) contributions from diagrams of $qg \to t\bar{t}q$ and $\bar{q}g \to t\bar{t}\bar{q}$ in Fig. 4. Pay attention that the above mentioned processes does not contain ultra-violet divergence so renormalization is unnecessary in the calculation. Moreover, $\sigma(|Y_t| < Y_{\rm C})$ and $\sigma(|Y_{\bar{t}}| < Y_{\rm C})$ contain collinear divergence respectively, but the divergences cancel completely out when calculating the asymmetric cross section. Soft divergences are contained in the former (1)virtual box and (2)real radiation contributions, but are canceled after adding the two. Technically a soft cut δ^s is introduced after the soft divergence cancelation[42]. The final results are δ^s-independent, which is carefully checked in our calculation.

III. NUMERICAL RESULTS

In the numerical calculations, the SM parameters are chosen to be $m_t = 170.9$GeV and $\alpha_S(m_Z) = 0.118$. We choose cteq6l for leading order calculation and cteq6m for NLO calculations. The scales are chosen as $\mu_r = \mu_f = m_t$.

Fig. 5 shows the numerical estimations for the LHC with $\sqrt{s} = 14$TeV. The left-up plot is the symmetric and asymmetric differential distribution as a function of the rapidity of t or $\bar{t}$. Notice that they are labeled in different scales. Also shown are the separate contributions

to symmetric cross section from $q\bar{q}$ and gg fusion processes. As can be seen the symmetric events dominantly come from the gg fusion processes and lie mainly in the small Y region. On the contrary the asymmetric cross section changes sign around $Y = 1.6$. Namely in the central region, the number of $\bar{t}$ events is larger than that of the t events. Oppositely, in the edge region, the number of t events is larger than that of the $\bar{t}$ events. This feature can be easily understood as following. The asymmetric cross section will be completely canceled out after integrating over the whole $Y > 0$ region. Therefore there should be a turning point where asymmetric cross section turns into the opposite sign. These behaviors can also be extracted from the right-up plot, which show the symmetric and asymmetric cross sections (cf. Eq. 2) as a function of Y_{C}. As a cross check, our result of the total leading order $t\bar{t}$ cross section is 548pb, which is consistent with the LO QCD prediction 583^{+165}_{-120} in Ref. [43]. In the left(right)-down plot in Fig. 5 we shown A_{E} (significance S_{E}) as a function of Y_{C} for several $Y_{max} = 2.4, 3.0, 5.0$ respectively. Significance is defined as $S = |N^A|/\sqrt{N} = \sqrt{\mathcal{L}}|A|\sqrt{\sigma}$. Here N^A (N) is the number of asymmetric (symmetric) events, and the integrated luminosity is chosen to be $\mathcal{L} = 10\mathrm{fb}^{-1}$ as an example. In the numerical estimations we take three Y_{max} values according to the coverage of the real detectors. $Y_{max} = 2.4$ is a conservative choice and $Y_{max} = 5.0$ is an optimal one. A_{C} (S_C) is also shown here. From the plots, we can see clearly the central asymmetry A_{C} is negative and the edge charge asymmetry A_{E} is positive. Moreover A_{E} is much larger than that of A_{C}. From curves A_{E} is usually several percentages while A_{C} is only $O(0.1)$ percentage. Significance is also a measure to determine the optimal choice of Y_{C}. The maximal significance for A_{C} and A_{E} with $Y_{max} = 2.4$ is almost the same. This is not strange because for A_{E} the event numbers for both symmetric and asymmetric are reduced greatly. Therefore the precision to measure A_{C} and A_{E} is similar. For the bigger rapidity coverage, the significance for A_{E} is much larger than that of A_{C} for the optimal Y_{C}. Based on the numerical studies, we can conclude that the detection for larger rapidity top quark is essential to measure A_{E} significantly.

Fig. 6 shows the same distributions as those in Fig. 5 except for $\sqrt{s} = 7$TeV. Due to the lower energy, the produced top pair events have smaller longitudinal boosts($Y < 3$). Thus curves with $Y_{max} = 3.0$ and 5.0 have small difference. The values of the asymmetries are larger than those of the 14TeV. They are mainly caused by two effects. First, at the parton level, a lower energy $\hat{s}$ can generate higher asymmetry. The parton level asymmetry distribution with $\hat{s}$ can be found in ref.[7]. This can be kept at the hadron level after the

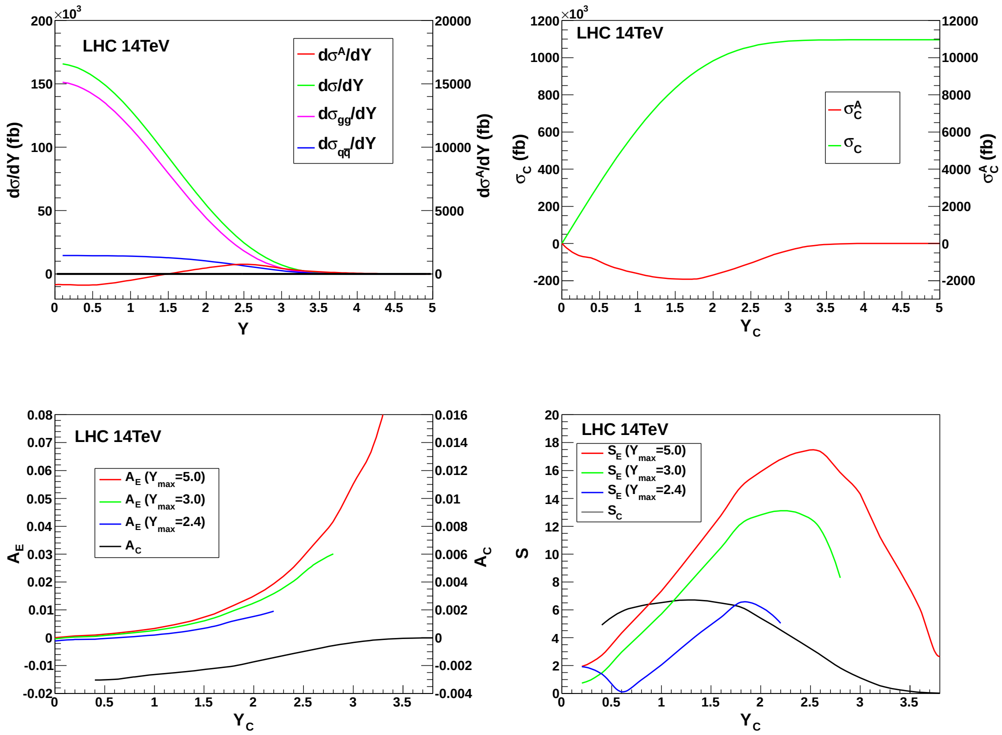


FIG. 5: Left-up plot: symmetric and asymmetric differential cross sections as a function of rapidity of top quark, and the separate contributions to symmetric cross sections from $q\bar{q}$ and gg fusions are also shown. Right-up plot: symmetric and asymmetric total cross sections in $A_{\rm C}$ (cf. Eq. 2) as a function of $Y_{\rm C}$. Left(Right)-down plot: $A_{\rm E}$ (significance $S_{\rm E}$ with integrated luminosity 10^{-1}fb, see text) as a function of $Y_{\rm C}$ for several $Y_{max} = 2.4, 3.0, 5.0$ respectively, $A_{\rm C}$ ($S_{\rm C}$) is also shown here. Here $\sqrt{s}$ at LHC is chosen as 14TeV and $d\sigma^A/dY$, $\sigma^A_{\rm C}$ and $A_{\rm C}$ are labeled in the right side of the plots due to their small values.

convolution of parton distribution function. Second, the portion of the symmetric $gg \to t\bar{t}$ process become smaller for a lower s. Thus the value of the charge asymmetry can be larger with a lower s than that with a higher s at the LHC.

From the figures we can also see that the significance of $A_{\rm E}$ at 7TeV is larger than that of $A_{\rm E}$ at 14TeV in the case $Y_{max} = 2.4$. The reason is that for the higher energy LHC, the top quarks tend to be highly boosted, which shifts the distribution of $d\sigma^A/dY$ to the higher rapidity. After imposing Y_{max} cut, the positive asymmetric cross section in the high rapidity region losts much. Thus with the same integrated luminosity the lower energy LHC has certain advantage to measure the top quark edge charge asymmetry in low Y_{max} case.

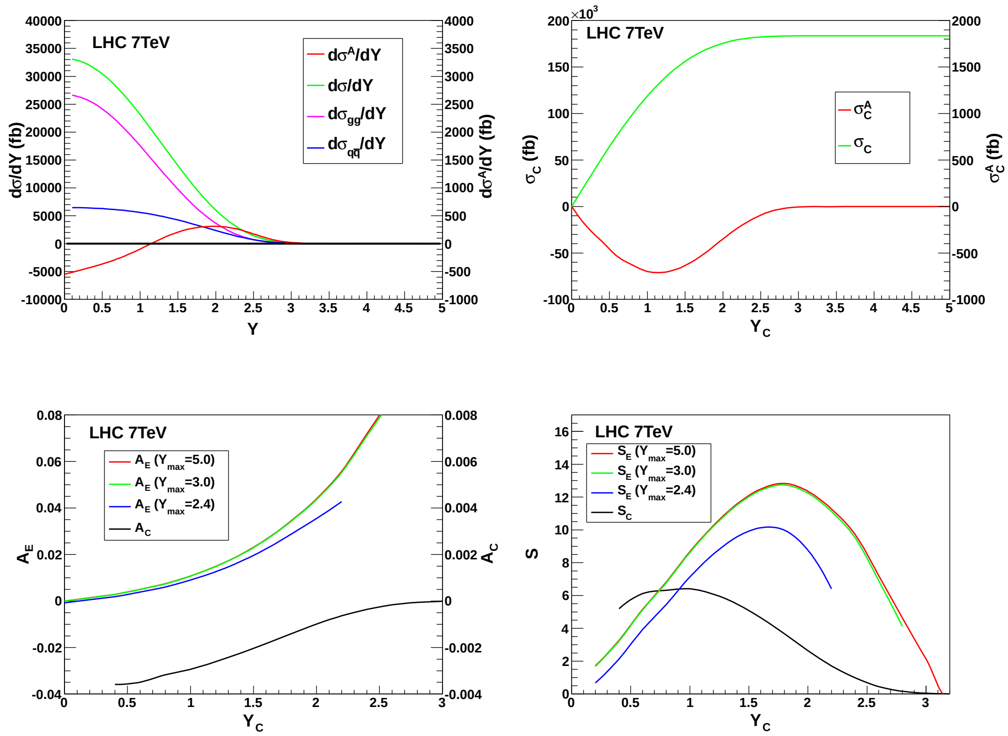


FIG. 6: Same as Fig.5 except for $\sqrt{s} = 7\text{TeV}$.

IV. CONCLUSIONS AND DISCUSSIONS

In this paper, we propose a new observable namely edge charge asymmetry A_E in top pair production at the LHC. A_E has two advantages: (1) free from the uncertainty arising from the missing neutrino in the $t\bar{t}$ event reconstruction because in the definition only single hadronically decaying top (or anti-top) kinematical information is needed; (2) suppressing greatly the symmetric $t\bar{t}$ events mainly due to the gluon-gluon fusion process. Our numerical estimation showed that A_E is much larger than that of central charge asymmetry A_C [6–8, 38]. Moreover the significance to measure the A_E is usually greater than that of A_C, provided that the capacity to identify high rapidity top quark is efficient.

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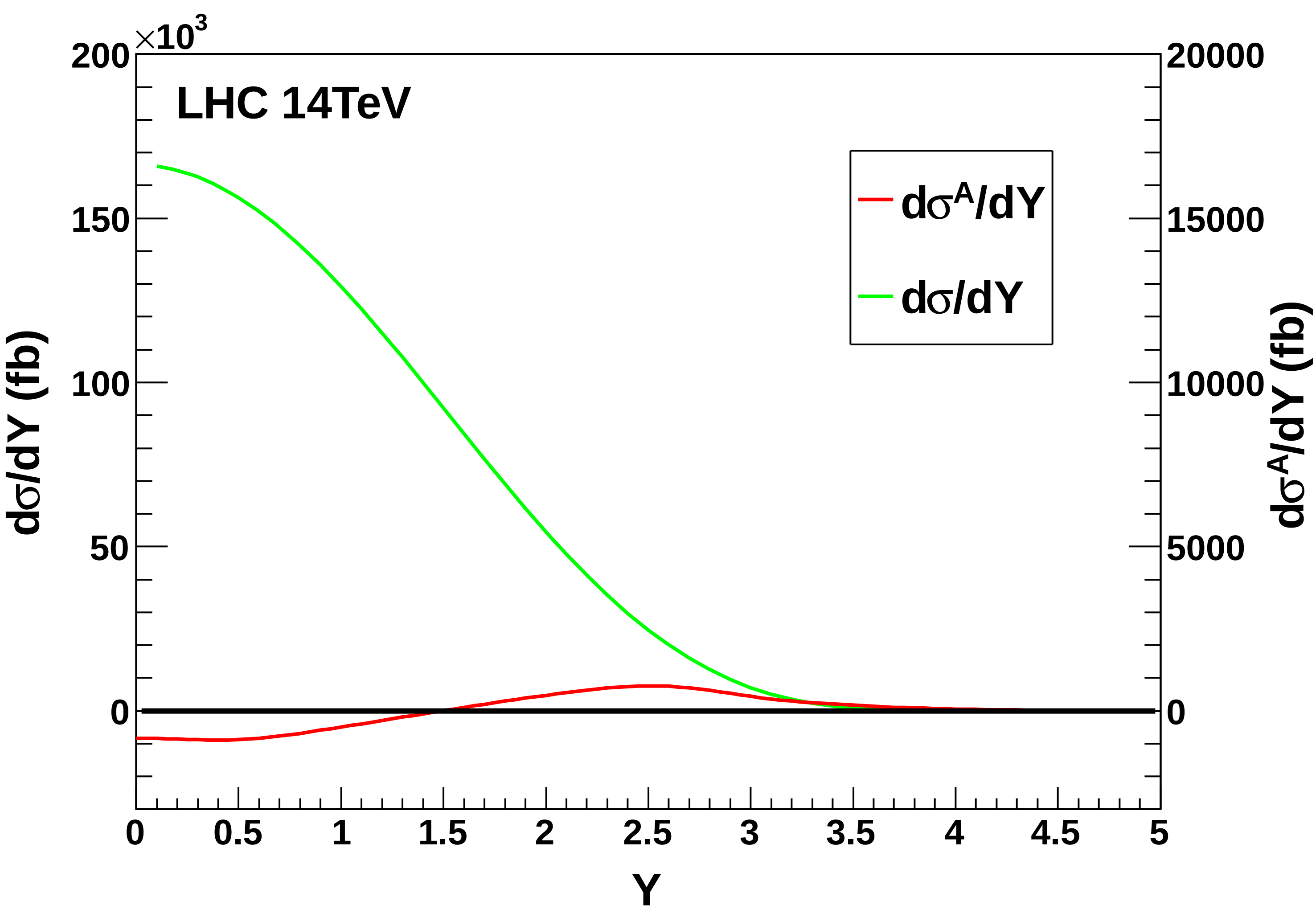

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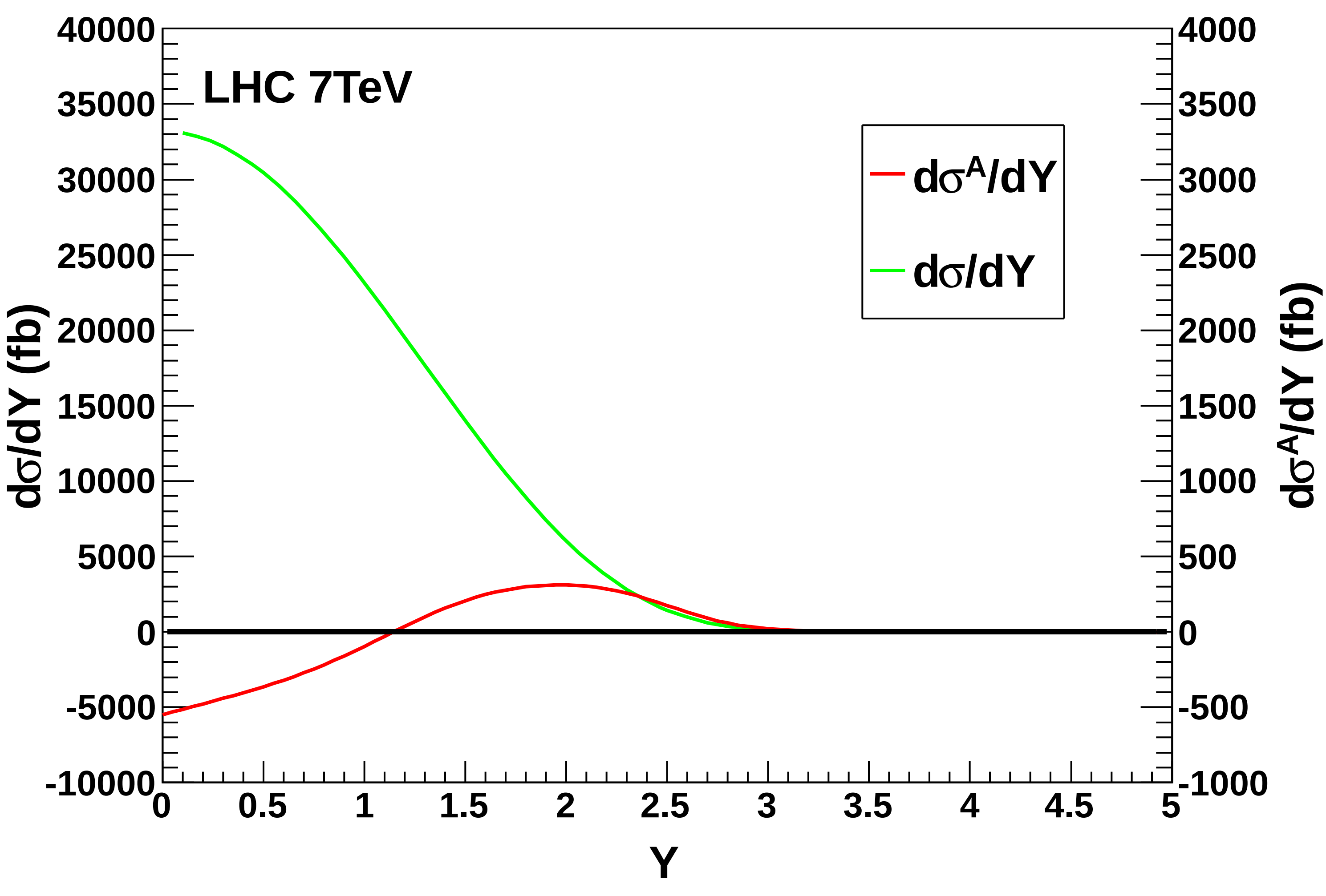

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